CHAPTER V

PLANT AND AIR TEMPERATURES IN
DIFFERENTIALLY IRRIGATED CORN

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ABSTRACT

Studies by Jackson et al. (1977) and Idso et al. (1977) indicate that wheat is not stressed for water unless leaf temperature exceeds air temperature. One objective of the study reported here was to evaluate the effects of varying levels of plant water stress and crop temperature with the aim of providing practical water resource management tools. The third objective was to determine relationships between leaf temperature and air temperature within corn canopies as a function of water stress.

Meteorological, physiological and phenological measurements were made in nine plots of corn (Zea mays L.), grown on Valentine fine sand (Typic ustipsamment) at the Sandhills Agricultural Laboratory (SAL). Each plot received one of seven different irrigation treatments. Canopy temperatures were measured with an infrared thermometer at mid-day throughout the growing season. Air and leaf temperature measurements were made on an hourly basis with thermocouples. Physiological and phenological observations were made weekly.

The average mid-day difference in canopy temperature between stressed and non-stressed areas was as large as 7.0 C. In fully irrigated plots, the standard deviation of mid-day canopy temperature was about 0.3 C but in non-irrigated areas it reached, at times, 4.2 C. We conclude that, a standard deviation of temperature in a plot, exceeding 0.3 C, signals that some plants

are experiencing water stress. This behavior can indicate the need for irrigation.

Daily profiles of leaf and air tempreature in stressed and non-stressed canopies were found to be similar. Profiles tended to be lapse before crop cover was complete and inverted later in the season. At any level within the stressed canopy, plants were warmer than at the same level within the non-stressed canopy. The mid-day temperature of sunlit leaves of non-stressed and moderately stressed plants was generally 1-2 C below air temperature. The temperature of sunlit leaves in severely stressed plants were as much as 4.6 C above air temperature. We observed that, contrary to some previously published results, corn plants may be subject to some water stress and still be cooler than the air temperature.

INTRODUCTION

The leaves of moisture stressed plants have been found to be warmer than those of non-stressed plants. Temperature differences between stressed and non-stressed leaves reported for various crops range from +2 to +8 C (Miller, 1923; Eaton, 1929; Millar et al., 1971; Ehrler et al., 1978).

Wiegand and Namken (1966) found that the difference in temperature between stressed and non-stressed cotton (Gossypium hirsutum L.) leaves ranged from 2.5 to 4.5 C when solar radiation flux density was 200 Wm^{-2} and 1100 Wm^{-2}, respectively.

Tanner (1963) suggested that the temperature difference between stressed and non-stressed potato (Solanum tuberosum) leaves gave a qualitative indication of their transpiration differences.

He concluded that, with a better understanding of heat and vapor transfer processes at the plant surface, leaf temperature measurements could provide quantitative data on plant water status.

Ehrler (1973) stated that long-term measurements of leaf temperature provide an indirect indication of stomatal behavior. Ehrler et al. (1978) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperature between stressed and non-stressed wheat plants were shown to be a reliable indicator of plant moisture status.

Clark (1973) stated that stomatal resistance in peas (Vigna sinensis L.) increased as moisture stress developed, resulting in increased leaf temperature. He concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution and other plant characteristics. Thus, for a true measure of plant moisture deficit, measurements should be made on the plant instead of in the soil or the atmosphere.

Aston and van Bavel (1972) and Nixon et al. (1973) suggest that a large variability in canopy temperature should signal the onset of soil moisture deficits due to the inhomogeneous moisure retention properties in large fields. Ehrler (1973) and Ehrler et al. (1978) showed that the differential in leaf-air temperature can be used to signal the need for irrigation. Ritchie (1977) suggested using the temperature difference between stressed and non-stressed plants to detect the occurrence of soil moisture deficits.

In view of the above-stated findings a study was designed

with the following objectives: 1) to evaluate the effects of
varying levels of plant water stress on crop temperatures; 2) to
establish the relationship between plant water stress and crop
temperature in corn with the aim of providing practical water
resource management tools (e.g. irrigation scheduling, drought
surveillance); and 3) to determine relationships between leaf
temperature and air temperature within corn canopies as a func-
tion of water stress.

METHODS AND MATERIALS

The study was conducted at the University of Nebraska Sand-
hills Agricultural Laboratory, located near Tryon, Nebraska (41°
47' N; 100° 50' W; 975 m above m.s.l.). Details of the experi-
mental site and research procedures are given in Chapter II.

Seven combinations of two basic irrigation treatments were
applied to nine plots of corn (Zea mays L. cv. Pioneer 3780)
(Table 1). The full irrigation treatment (I) consisted of re-
supplying by irrigation 100% of the water used to all rows in
a plot. The amount of water consumed by evapotranspiration was
determined by measuring soil moisture depletions with a neutron
probe. The gradient treatment (G) consisted of applying full
irrigation to row 1 of a plot and applying progressively less
moisture to each succeeding row, until rows 22 through 24 received
essentially no irrigation.

Canopy temperatures were measured with an infrared thermo-
meter (IRT) each day between 1200 and 1330 solar time on rows 2,
6, 10, 14, 18 and 22 and of each plot. Readings began on June 1
and continued throughout the growing season, except for a few days

Table 1. The seven irrigation treatments used for the study. I
means that all rows in a plot received a full irrigation
during that growth period. G means that an irrigation
gradient was established so that one side of the plots
received 100% of its water needs, while the opposite side
received essentially none of its needs.

| | Growth Stage | | |
Treatment	Vegetative	Pollination	Grain Filling
1	G	I	I
2	I	G	I
3	I	I	G
4	G	I	G
5	I	G	G
6	G	G	G
7	G	G	I

when measurement was not possible. Two infrared thermometers were used. A Telatemp model 44 was used between June 13 and July 17. A Barnes model PRT-5 was used for the remainder of the season. The maximum width of the spot seen by the IRT's was calculated to be 95 cm and the maximum length 200 cm. The viewing angle decreased from about 22 to about 15 degrees from the horizontal as the crop increased in height.

Detailed measurements of leaf and air temperature profiles were made in one plot (hereafter, called the instrumented plot). Air and leaf temperatures were measured at 3 different levels within the canopy in rows 2, 6, 10, 14, 18 and 22. The bottom, middle and top of the canopy were designated levels 1, 2 and 3, respectively. Air thermocouples in levels 2 and 3 were raised as the crop grew. The crop reached its full height by July 26 and no further adjustments in instrument height were made after that date.

Leaf temperatures were measured at each level with a set of 5 or 6 evanohm-constantan thermocouples (0.13 mm diameter) which were wired in parallel. The junctions of each thermocouple junction were taped to the lower surface of different leaves, using the method described by Steinmetz (1977).

Copper-constantan air thermocouples, in 6 mm diameter teflon plugs to dampen rapid fluctuations in air temperature, were placed in level 3. One air thermocouple was mounted permanently at a height of 3 meters above ground in row 2.

RESULTS AND DISCUSSION

Temperature Differences Between Stressed and Non-Stressed Areas

The average mid-day IRT-measured temperature difference between row 22 and row 2 (notated as $*T_{22} = T_{22} - T_2$) was larger on gradient (G) plots than on fully irrigated (I) plots. This effect is noted during the vegetative (Fig. 1), the pollination (Fig. 2) and the grain-filling (Fig. 3) periods. Another note-worthy feature is the greater standard deviation of $*T$ (σ_T) in G and in I plots.

σ_T, which represents the mid-day spatial variability in canopy temperature, averaged 1.0 C on I plots and 1.2 C on G plots prior to July 10 (approximately full plant cover). After July 10, σ_T decreased to 0.3 C on I plots but remained about 1.2 C on G plots (Table 2), though on some days σ_T on G plots was as great as 4.2 C. The large temperature variability in the G plots results from microscale variations in soil water retention characteristics and from differences in the amount of irrigation applied to row 22 at various growth stages. In some G plots row 22 was fully irrigated during a previous growth period but in some plots it had received no irrigation. On several days during the pollination period σ_T was small because of cool, cloudy and wet weather.

Inspection of Fig. 1 indicates that rainfall or irrigation had only a minor effect on σ_T during much of the vegetative period. However, during the late vegetative, pollination and grain-filling periods, σ_T on well-irrigated plots increased prior to irrigation and decreased after irrigation on July 13, July 26, August 17 and September 1.

Heermann and Duke (1978) found that σ_T in well-irrigated corn
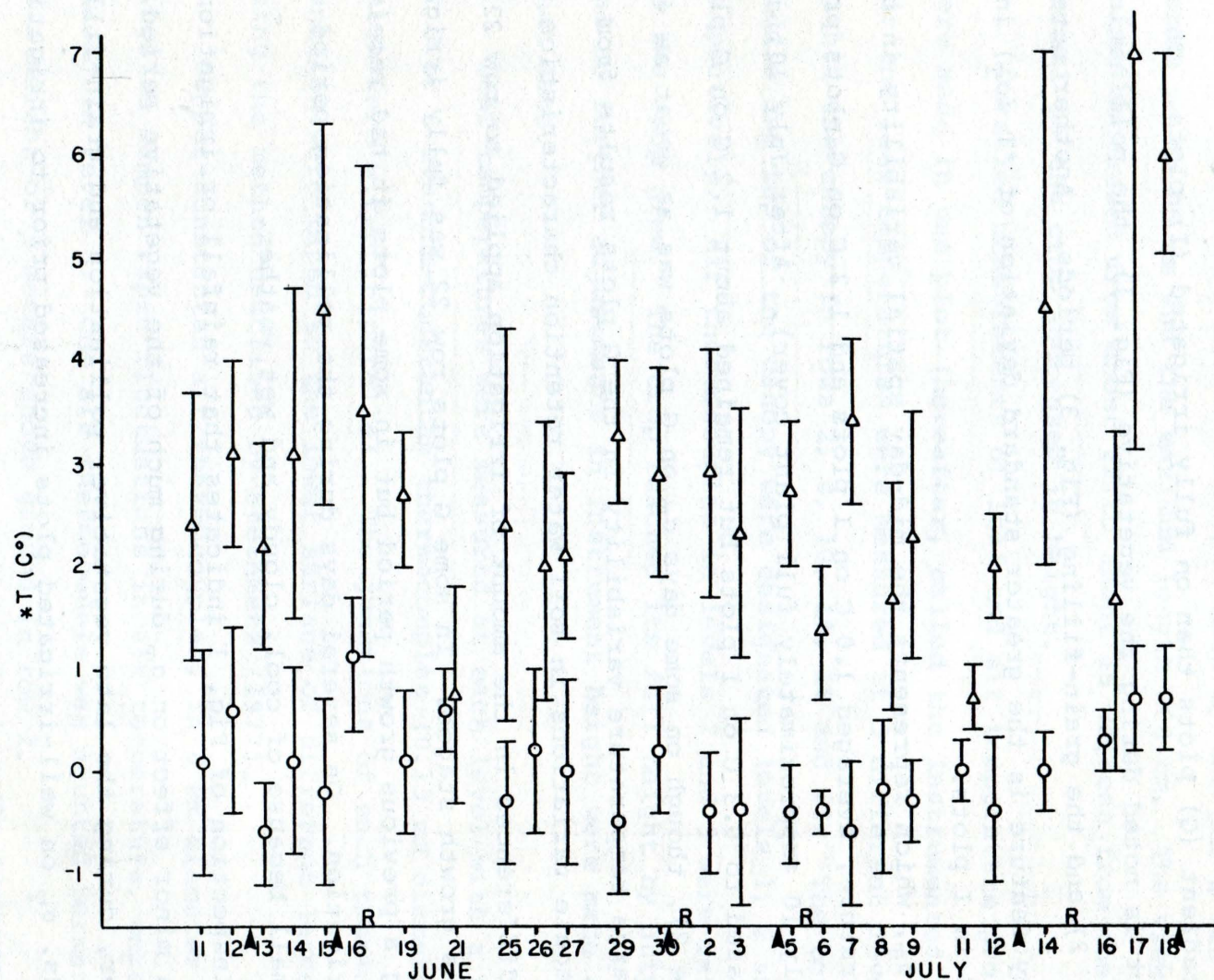
Fig. 1. The average difference in mid-day canopy temperature between row 22 and row 2 (*T) on plots receiving a gradient treatment (Δ) and in fully irrigated plots (o) during vegetative growth. Standard deviation (σ_T) of each data point is indicated with a bar. The occurrence of rainfall is indicated with an R and irrigations are indicated with arrows.
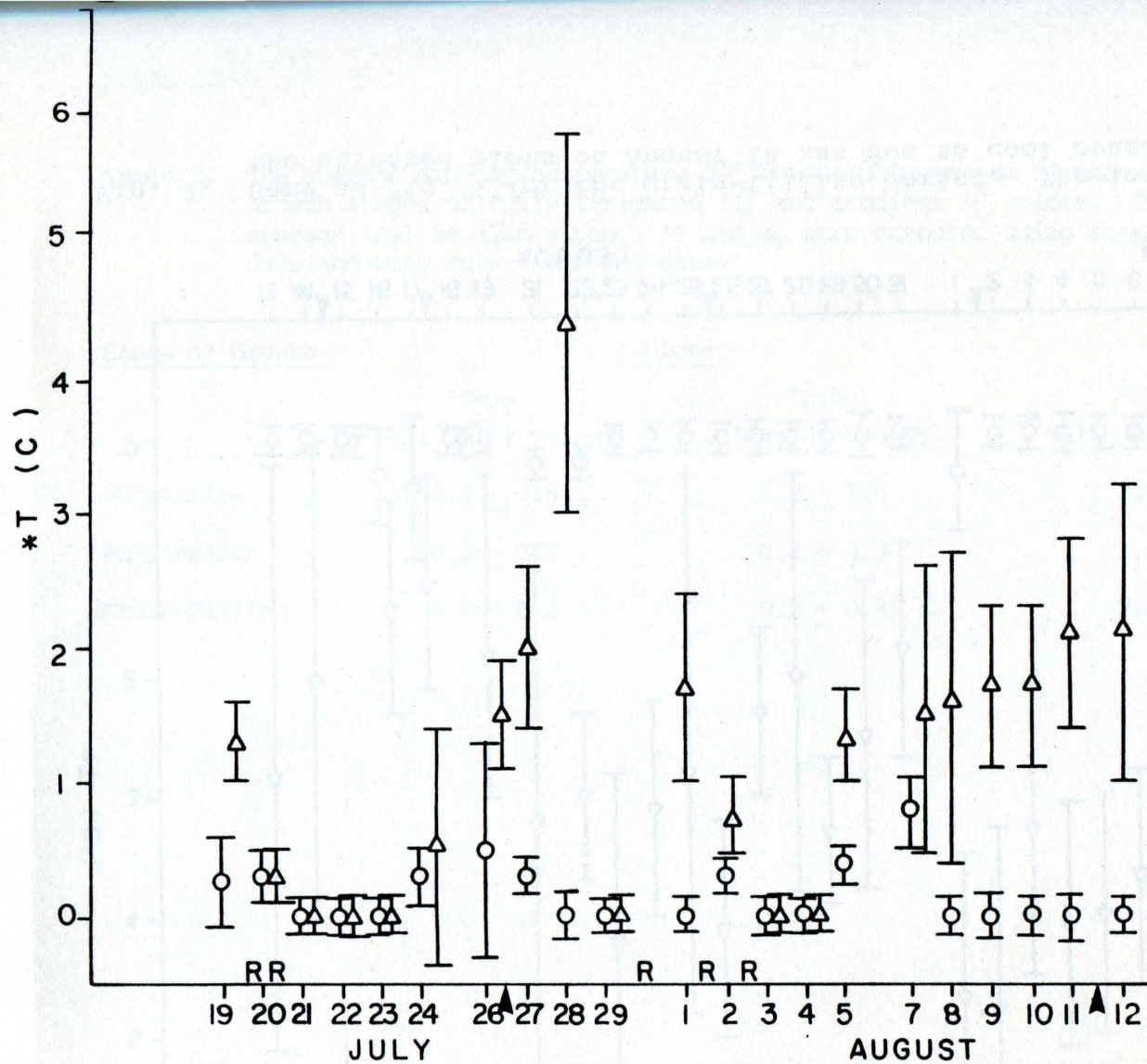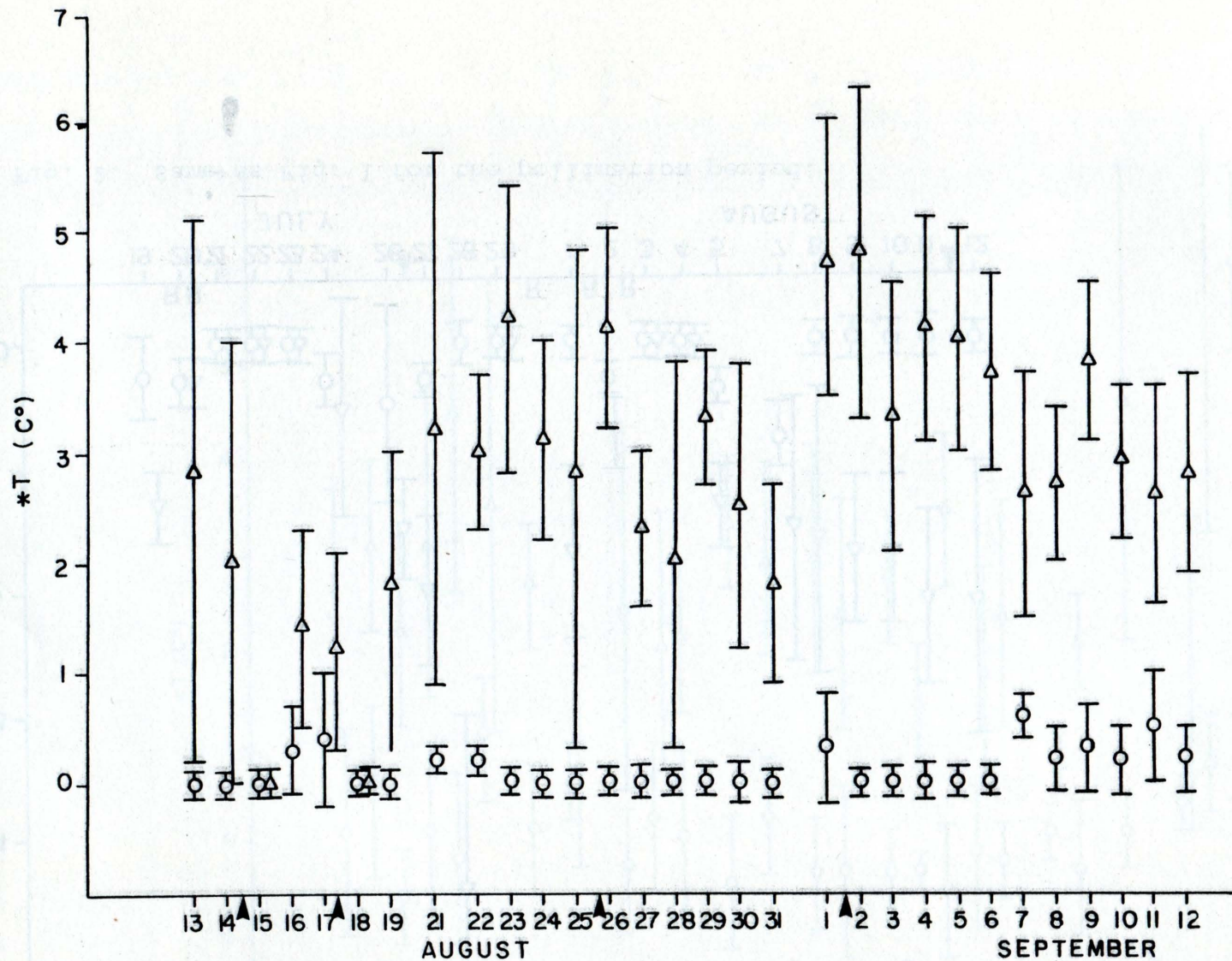
Fig. 2.   Same as Fig. 1 for the pollination period.

Fig. 3. Same as Fig. 1 for the grain-filling period. The low *T and σ_T value for the stressed plots on August 18 was due to cool overcast weather.

Table 2. The average mid-day temperature difference between row 22 and row 2 (*T) for the different growth stages of fully irrigated (I) and gradient (G) plots. The standard deviation of each average (σ_T) is also given. *T and σ_T were computed using crop temperatures obtained on all days and with only clear day data.

Stage of Growth	I Plots		G Plots	
	*T+σ_T (All daily values)	*T+σ_T (clear days only)	*T+σ_T (All daily values)	*T+σ_T (clear days only)
Vegetative	0.4 + 0.8	0.2 + 1.0	2.9 + 1.3	2.7 + 1.12
Pollination	0.2 + 0.3	0.2 + 0.3	1.2 + 1.1	1.8 + 1.0
Grain-Filling	0.1 + 0.2	0.2 + 0.3	2.8 + 1.2	3.1 + 1.1

at oblique viewing angles was around 0.2 C but at vertical view-
ing angles σ_T was approximately 1.5 C. σ_T may change as a function
of soil type and crop, as well as IRT viewing angle. At the
oblique IRT viewing angles used in this study values of σ_T above
0.3 C resulted when some plants began to experience water stress.

On the basis of these findings, it appears that the irriga-
tions on July 13, July 26 and August 17 were a day or so too late
to prevent stress in the well-watered plots, while the irrigation
of September 1 was timely - applied as it was on the evening of
the day on which stress was first observed. The irrigations of
August 11, 14 and 25 were made prior to the appearance of plant
stress. All irrigations had been scheduled with the aid of the
neutron probe. That method, apparently, gave satisfactory results.

These findings suggest the possibility of using *T and σ_T
measurements to evaluate and compare the effectiveness of various
methods for scheduling irrigation and for evaluating the uniformity
of water application with different irrigation systems and techni-
ques. If these measurements can be made from aircraft or satellite
platforms they may also offer the potential for evaluating the
severity of drought on a regional basis. The use of σ_T to schedule
irrigations also offers possibilities. When σ_T increased above
the average expected value - 0.3 C in this study - the need for
irrigation was indicated.

Plant Temperature as an Indicator of Severity of Stress

Differences in temperature between stressed and non-stressed
areas did not begin to develop, typically, until after 1100 solar
time. However, on September 1, in the instrumented plot, $*T_{22}$ was

1.5 C at 0800 and 3.5 C at 0900 hrs, indicating tht stomata were
already closing on the plants in row 22. This probably reflects
an increase in the severity of water stress experienced by the
plants and suggests that *T measurements may be used, as well,
to distinguish the degree of plant water stress. This hypothe-
sis is explored in further detail in Chapter VIII.

Daily Patterns of Leaf and Air Temperature

     Before crop cover was complete in the instrumented plot,
the leaf temperature profiles tended to be isothermal in both
stressed and non-stressed areas during the day. Temperature
differences across the plot occurred at each level within the
canopy. After crop cover was complete the leaf temperature
profiles during the day were generally inverted. This was due,
primarily, to the absorption of solar radiation by leaves near
the top of the canopy and the shading of leaves within the canopy.
Differences in leaf temperatures at each level with the canopy
across the plot persisted because of reduced transpiration in the
water stressed plants.

     A typical daily pattern of thermocouple measured leaf and
infrared measured canopy temperatures under conditions of clear
skies with moderately strong winds is given in Fig. 4. Canopy
temperatures measured with the IRT closely followed the tempera-
ture of sunlit leaves (level 3) in both the stressed and non-
stressed areas (row 22 and row 2, respectively).

     The vertical air temperature gradients (Fig. 5), in the non-
stressed row (2) followed the same pattern as the leaf temperature
gradients, that is both were inverted. However, in the more open
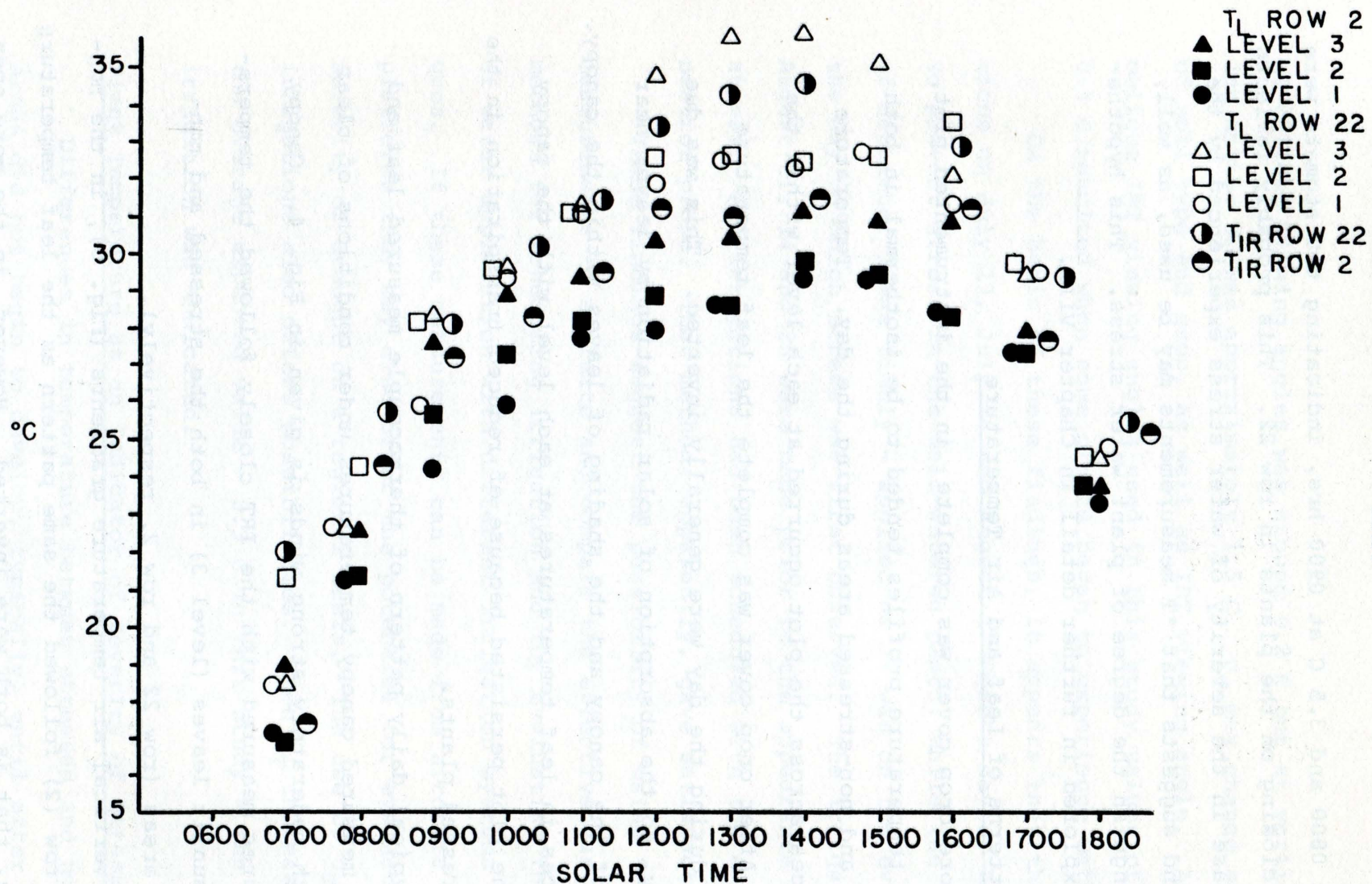
Fig. 4. Daily pattern of leaf temperatures on August 22, 1978, in row 2 (non-stressed) and row 22 (stressed) at the bottom of the canopy (level 1), middle of the canopy (level 2) and at the top of the canopy (level 3). Infrared canopy temperatures (T_{IR}) are also plotted.
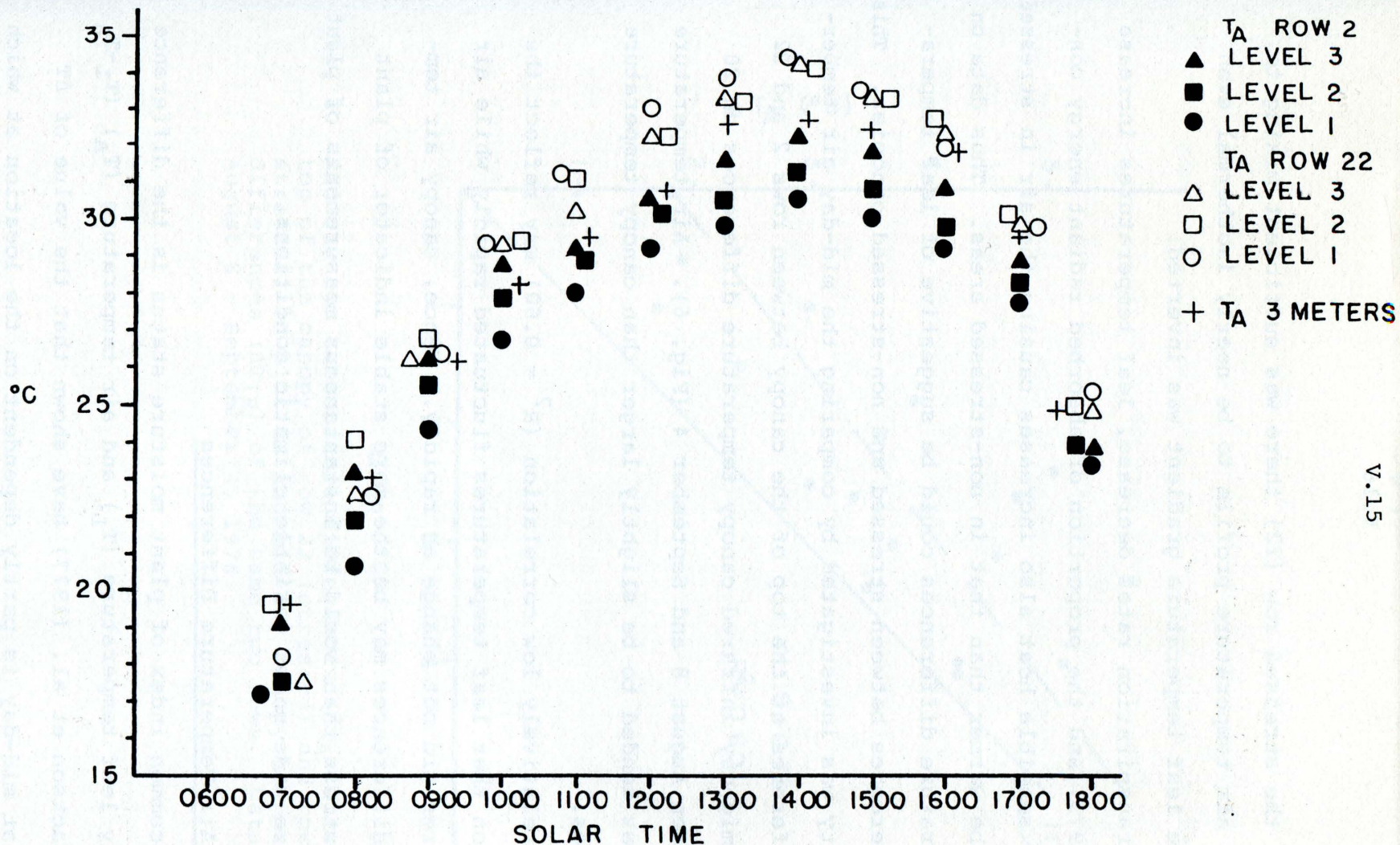
Fig. 5. Daily pattern of air temperature (T_A) on August 22, 1978, in row 2 and row 22 at the bottom of the canopy (level 1), the middle of the canopy (level 2) and at the top of the canopy (level 3). Air temperature at three meters above the soil surface in row 2 is included.

canopy in the stressed row (22) there was sufficient mixing to cause the air temperature profile to be nearly isothermal even though the leaf temperature gradient was inverted.

As transpiration rates decrease, leaf temperatures increase (Hsaio, 1973) and the proportion of absorbed radiant energy converted to sensible heat also increases causing the air in stressed areas to be warmer than that in non-stressed areas. Thus data on air temperature differences could be suggestive of leaf temperature differences between stressed and non-stressed canopies. This possibility was investigated by comparing the mid-day air temperature difference at the top of the canopy between rows 2 and 22 with the mid-day infrared canopy temperature differences on 20 days between August 8 and September 4 (Fig. 6). Air temperature differences tended to be slightly larger than canopy temperature differences.

The relatively low correlation (R^2 = 0.60) may reflect the observation that leaf temperatures fluctuated rapidly while air temperatures did not change as rapidly. Hence, canopy air temperature differences may be the more stable indicator of plant moisture stress than would be instantaneous measurements of plant temperature made under variable climatic conditions.

Leaf and Air Temperature Differences

One common index of plant moisture status is the difference in mid-day leaf temperature (T_L) and air temperature (T_A) (T_L-T_A = ΔT). Jackson et al. (1977) have shown that the value of ΔT obtained at mid-day is partly dependent on the location at which air temperature (T_A) is measured. Accordingly, we computed ΔT
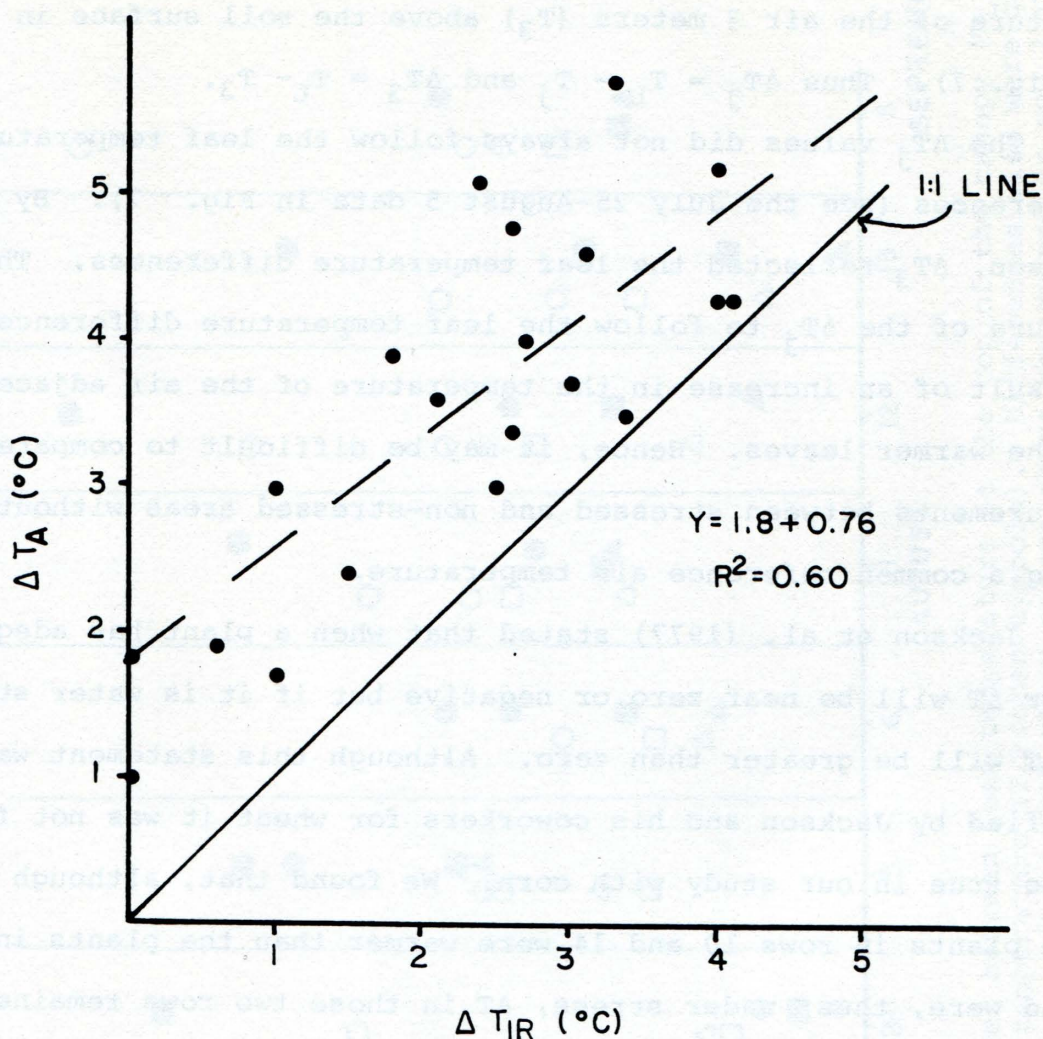
Fig. 6. Mid-day air temperature differences (ΔT_A) between the top of the canopy of row 22 (stressed) and row 2 (non-stressed) in plot 22 and mid-day canopy temperature differences (ΔT_{IR}) of the same two rows. Data are from August 8 - September 4, 1978.

of leaves at the top of the canopy in rows 2, 10, 14 and 22 using the temperature of the adjacent air (T_j) in each row or the temperature of the air 3 meters (T_3) above the soil surface in row 2 (Fig. 7). Thus $\Delta T_j = T_L - T_j$ and $\Delta T_3 = T_L - T_3$.

The ΔT_j values did not always follow the leaf temperature differences (see the July 25-August 5 data in Fig. 7). By comparison, ΔT_3 reflected the leaf temperature differences. The failure of the ΔT_j to follow the leaf temperature differences is a result of an increase in the temperature of the air adjacent to the warmer leaves. Hence, it may be difficult to compare ΔT measurements between stressed and non-stressed areas without using a common reference air temperature.

Jackson et al. (1977) stated that when a plant has adequate water ΔT will be near zero or negative but if it is water stressed ΔT will be greater than zero. Although this statement was verified by Jackson and his coworkers for wheat it was not found to be true in our study with corn. We found that, although the corn plants in rows 10 and 14 were warmer than the plants in row 2 and were, thus, under stress, ΔT in those two rows remained negative. Only in row 22 was ΔT found to be positive. In Chapter II it was shown that yields were reduced in proportion to the degree of stress experienced by the plants in rows 10 and 14. These results suggest that corn is probably more sensitive to water stress than is wheat and that the use of ΔT values to indicate water stress are probably soil, crop and climate specific.
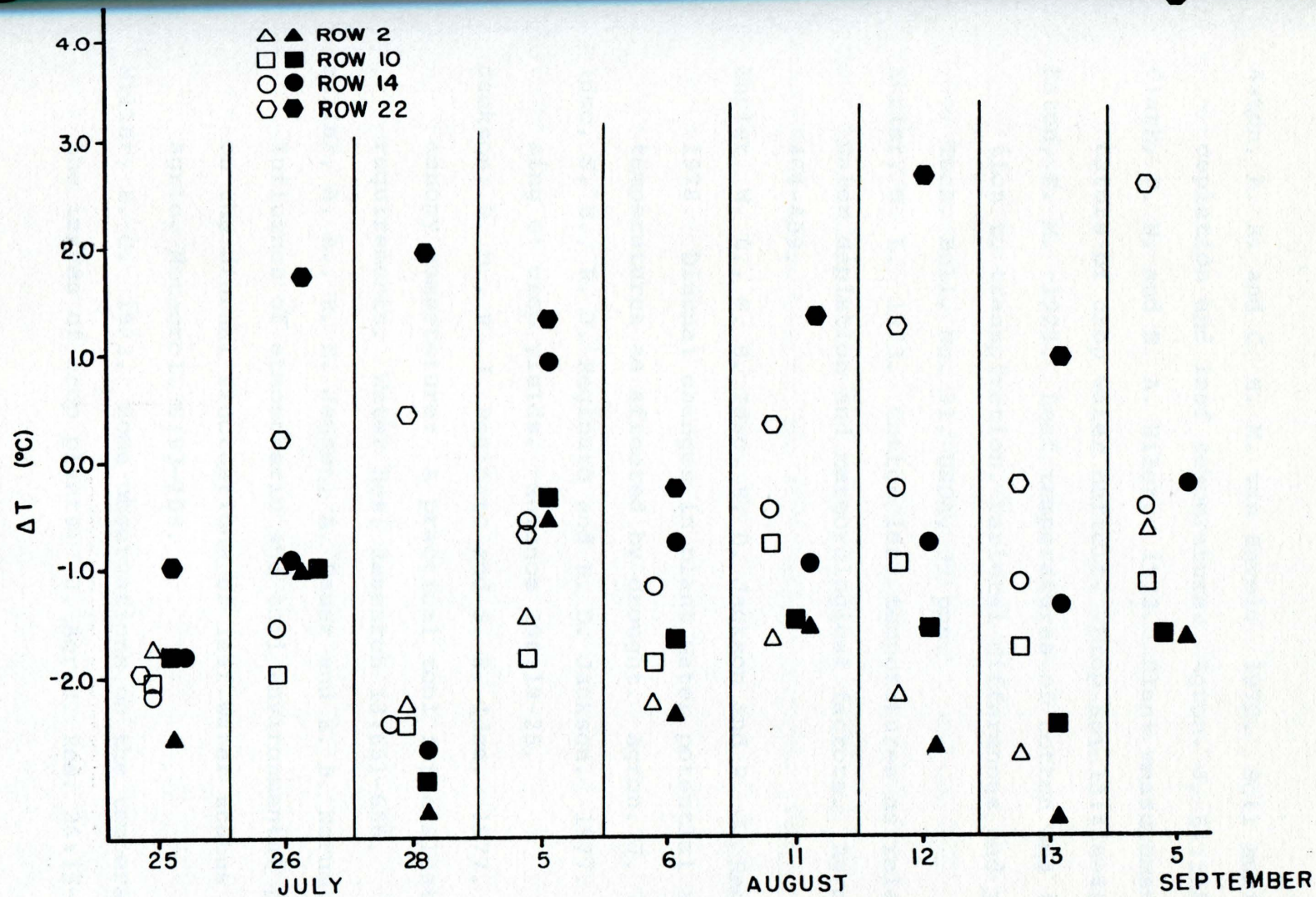
Fig. 7. Mid-day differences between leaf temperature at the top of the canopy (T_L) and adjacent air temperature (T_j) (open symbols). Differences also were computed using air temperature from three meters above the ground in row 2 (T_3) (closed symbols). Calculations were performed on data from rows 2, 10, 14 and 22 on plot 22 for nine clear days between July 25 and September 5, 1978.

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